CHAPTER 10

BRIDGES

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10.1 INTRODUCTION

10.1.1 Definition

Bridges are defined as:

- structures that transport traffic over waterways or other obstructions;

- part of a stream crossing system that includes the approach roadway over the floodplain, relief openings and the bridge structure; and

- legally, structures with a centerline span of 20 ft or more. However, structures designed hydraulically as bridges as described above are treated in this Chapter, regardless of length.

10.1.2 Analysis/Designs

Proper hydraulic analysis and design is as vital as the structural design. Stream crossing systems should be designed for:

- minimum cost subject to design criteria;
- desired level of hydraulic performance up to an acceptable risk level;
- mitigation of impacts on the stream environment; and
- accomplishment of social, economic and environmental goals.

10.1.3 Purpose of Chapter

1. Provide guidance in the hydraulic design of a stream crossing system through:

    - appropriate policy and design criteria, and
    - appropriate design procedures.

2. Present non-hydraulic factors that influence design including:

    - environmental concerns;
    - emergency access and traffic service; and
    - consequences of catastrophic loss.

3. Present a design procedure that emphasizes hydraulic analysis using suitable computer programs such as WSPRO or HEC-RAS.

4. Present a brief section on design philosophy. A more in-depth discussion is presented in Reference *(1)*.

10.2 POLICY

10.2.1 General Policy

Policies that are unique to bridge crossings are presented in this Section.

The hydraulic analysis should consider various stream crossing system designs to determine the most cost-effective proposal consistent with design constraints.

Policy provides guidelines subject to change as approved by UDOT.

10.2.2 Agency Policy

These policies identify specific areas for which quantifiable criteria can be developed:

- The final design selection should consider the maximum backwater and encroachment limits allowed by the National Flood Insurance Program (NFIP), unless exceedence of the limit can be justified by special hydraulic conditions.
- The final design should not significantly alter the flow distribution in the floodplain.
- The “crest-vertical curve profile” should be considered as the preferred highway crossing profile when allowing for roadway overtopping at a lower discharge.
- A specified clearance should be established to allow for passage of ice and debris. For navigational channels, a vertical clearance conforming to Federal requirements should be established based on normally expected flows during the navigation season.
- Degradation or aggradation of the river and contraction and local scour shall be estimated, and appropriate positioning of the foundation, below the total scour depth if practicable, shall be included as part of the final design.
- Final design should be reviewed by using a check flood 500-yr to determine any significant impacts to the highway facility and adjacent property.

10.3 DESIGN CRITERIA

10.3.1 General Design Considerations

The following items should be considered when performing a hydraulic analysis for the location and design of bridges over waterways:

- The backwater shall not significantly increase flood damage to property upstream of the crossing.
- The velocities through the structure(s) shall not damage the highway facility nor increase damages to adjacent property.
- The bridge design shall maintain the existing flow distribution as practicable.
- The pier spacing and orientation and abutment alignment and shape shall be designed to minimize flow disruption and potential scour.
- The foundation shall be designed and, where required, shall include scour countermeasures to avoid foundation failure by scour.
- The design freeboard at structure(s) shall consider passage of anticipated debris and ice.
- The bridge design shall either accommodate acceptable risks of damage or include viable measures to counter the vagaries of alluvial streams.

- The bridge design shall minimize disruption of ecosystems and values unique to the floodplain and stream.

- The bridge design shall provide a level of traffic service compatible with that commonly expected for the class of highway and compatible with projected traffic volumes.

- The bridge design choices should support costs for construction, maintenance and operation, including probable repair and reconstruction and potential liability, that are affordable.

10.3.2 Agency Criteria

These criteria augment the general design considerations. They provide specific, quantifiable values that relate to local site conditions. Evaluation of various alternatives according to these criteria can be accomplished by using the water surface profile computer programs.

10.3.2.1 Traveled Way

Inundation of the traveled way dictates the level of traffic service provided by the facility. The traveled way overtopping flood level identifies the limit of serviceability. Desired minimum levels of protection from traveled way inundation for functional classifications of roadways are presented in Chapter 7.

10.3.2.2 Risk Evaluation

The selection of hydraulic design criteria for determining the waterway opening, roadway grade, scour potential, riprap and other features shall consider the potential impacts to:

- traffic,
- adjacent property,
- the environment,
- the infrastructure of the highway, and
- UDOT minimum level of flood protection.

The consideration of the potential impacts constitutes an assessment of risk for the specific site. The least-total-expected-cost (LTEC) alternative should be developed in accordance with HEC 17 (Reference *(3)*), where a need for this type of analysis is indicated by the risk assessment. This analysis provides a comparison between other alternatives developed in response to considerations such as environmental, regulatory and political. See Section 10.6.7.

10.3.2.3 Design Floods

Design floods for such factors as the evaluation of backwater, clearance and overtopping shall be established predicated on a risk-based assessment of local site conditions. The risk assessment shall reflect consideration of traffic service, environmental impact, property damage, hazard to human life and floodplain management criteria. Traveled way inundation from Chapter 7, Appendix 7.A, which represents a frequency-based design, shall be used to establish the minimum design flood.

10.3.2.4 Backwater/Increases Over Existing Conditions

The hydraulic design shall conform to FEMA and State regulations or local ordinances for stream crossings with flood elevations provided by the National Flood Insurance Program's studies. Not to exceed 1 ft during the passage of the 100-yr flood, if practicable for sites not covered by NFIP.

10.3.2.5 Clearance

Where practicable, a minimum clearance of 2 ft shall be provided between the design approach water surface elevation and the low chord of the bridge to allow for passage of ice and debris. Where this is not practicable, the clearance should be established by the hydraulics engineer based on the type of stream and level of protection desired as required by the Department.

10.3.2.6 Flow Distribution

The conveyance of the proposed stream-crossing location shall be calculated to determine the flow distribution and to establish the location of the bridge opening(s). The proposed facility shall not cause any significant change in the existing flow distribution. Relief openings in the approach roadway embankment or other appropriate measures shall be investigated, if there is more than a 10% redistribution of flow.

10.3.2.7 Scour

Design for bridge foundation scour considering the magnitude of flood, including the 100-yr event, that generates the maximum scour depth. The design shall use a geotechnical design practice safety factor of from 2 to 3. The resulting design should then be checked using a super flood 500-yr and a geotechnical design practice safety factor of at least 1.0. See Section 10.6.8.

10.4 DESIGN PROCEDURE

10.4.1 Survey Accuracy (Computation Method)

The design for a stream-crossing system requires a comprehensive engineering approach that includes the formulation of alternatives, data collection, selection of the most cost-effective alternative according to established criteria and documentation of the final design.

Water surface profiles are computed for a variety of technical uses including:

- flood insurance studies,
- flood hazard mitigation investigations,
- drainage crossing analyses, and
- longitudinal encroachments.

The computed water surface profile is used to establish the highway bridge length and elevation and is the basis for determining the effect of a bridge opening on upstream water levels. Errors associated with computing water surface profiles with the step-backwater profile method can be classified as:

- data estimation errors resulting from incomplete or inaccurate data collection and inaccurate data estimation,

- errors in accuracy of energy loss calculations and the accuracy of the energy loss coefficients,
- inadequate length of stream reach investigated, and
- significant computational errors resulting from excessive distances between cross sections. Errors can result from inaccurate integration of the energy loss-distance relationship. These errors may be reduced by adding interpolated or actual sections (more calculation steps).

10.4.2 Design Procedure Outline

The following design procedure outline shall be used. Although the scope of the project and individual site characteristics make each design unique, this procedure shall be applied unless indicated otherwise by the Department:

I. Data Collection

A. Survey
- Topography
- Geology
- High-water marks
- History of debris accumulation, ice and scour
- Review of hydraulic performance of existing structures
- Maps and aerial photographs
- Rainfall and stream gage records
- Field reconnaissance

B. Studies by other agencies
- Federal Flood Insurance Studies
- Federal Floodplain Studies by USACE, USGS and NRCS.
- State Agency and Local Floodplain Studies
- Hydraulic performance of existing bridges
- USGS

C. Influences on hydraulic performance of site
- Other streams, reservoirs and water intakes
- Structures upstream or downstream
- Natural features of stream and floodplain
- Channel modifications upstream or downstream
- Floodplain encroachments
- Sediment types and bed forms (Also see Appendix C, Scour, Site Data, Level I Qualitative Analysis — HEC 20 *(8)*)

D. Environmental impact
- Existing bed or bank instability (Level I)
- Floodplain land use and flow distribution
- Environmentally sensitive areas (fisheries and wetlands)
- Level I Qualitative Analysis (HEC 20 *(8)*)

E. Site-Specific Design Criteria
   - Preliminary risk assessment
   - Application of agency criteria

II. <u>Hydrologic Analysis</u>

A. Watershed morphology
   - Drainage area to be shown on attached map
   - Watershed and stream slope
   - Channel geometry

B. Hydrologic computations
   - Discharge and frequency for historical flood that complements the high-water marks used for calibration
   - Discharges for specified frequencies

III. <u>Hydraulic Analysis</u>

A. Computer model calibration and verification
B. Hydraulic performance for existing conditions
C. Hydraulic performance of proposed designs
D. Scour computations

IV. <u>Selection of Final Design</u>

A. Risk assessment/least-total-expected-cost alternative (LTEC)
B. Measure of compliance with established hydraulic criteria
C. Consideration of environmental and social criteria
D. Design details (e.g., riprap, scour abatement, river training)

V. <u>Documentation</u>

A. Complete project records and permit applications
B. Complete correspondence and reports

Checklist and Risk Assessment forms are presented in Appendix 10.A.

10.4.3 Hydraulic Performance of Bridges

Open channel flows are classified as steady or unsteady. Unsteady flow is further classified as rapidly or gradually varied. Additionally, flow through a stream crossing system is subject to either free-surface or pressure flow through one or more bridges with possible roadway overtopping.

Most open channel flows in nature are unsteady with some aspects of the flow such as depth or velocity changing with time. Because unsteady flow solutions can be very complicated and time consuming, these problems have typically been solved by assuming a steady flow condition. The result is an approximate solution that is adequate for certain types of planning or design hydraulic problems but that is inadequate for many other types of problems (e.g., crossings of streams that have broad floodplains).

Gradually varied, unsteady flow creates a water surface profile wave with mild curvature and a gradual change in depth. Whereas in rapidly varying, unsteady flow, the change in depth is large, and the curvature of the profile is very sharp. Typically, flow through a bridge is rapidly varying, unsteady flow.

Flow through bridges may be computed using a one-dimensional or a two-dimensional model. A one-dimensional approach determines the flow rate through the bridge on the basis of the water surface elevations at the upstream and downstream sides of the structure assuming steady, gradually varied flow conditions. Where conditions at the site depart significantly from these assumptions, such as streams with broad floodplains where storage and acceleration effects could be substantial or where pressure flow in possible combination with overtopping flow may be present, a two-dimensional model should be considered.

It is impracticable to perform the hydraulic analysis for a bridge by manual calculations due to the flow complexities being simulated and the interactive, complex nature of the calculations involved. These analyses should be compiled using an appropriate computer program. Although the most often used programs provide a one-dimensional solution, it is increasingly more practicable to use two-dimensional models to analyze unsteady, rapidly varying flow conditions at hydraulic structures.

The basic hydraulic variables and flow types are defined in Figures 10-1 and 10-2 and discussed as follows:

- Backwater (h_1) is measured relative to the normal water surface elevation without the effect of the bridge at the approach cross section (Section 1). It is the result of contraction and re-expansion head losses and head losses due to bridge piers. Backwater can also be the result of a “choking condition,” in which critical depth is forced to occur in the contracted opening with a resultant increase in depth and specific energy upstream of the contraction. This is illustrated in Figure 10-2.

- Type I flow consists of subcritical flow throughout the approach, bridge and exit cross sections and is the most common condition encountered in practice.

- Types IIA and IIB flows both represent subcritical approach flows that have been choked by the contraction resulting in the occurrence of critical depth in the bridge opening. In Type IIA, the critical water surface elevation in the bridge opening is lower than the undisturbed normal water surface elevation. In Type IIB, it is higher than the normal water surface elevation, and a weak hydraulic jump immediately downstream of the bridge contraction is possible.

- Type III flow is supercritical approach flow and remains supercritical through the bridge contraction. Such a flow condition is not subject to backwater, unless it chokes and forces the occurrence of a hydraulic jump upstream of the contraction.

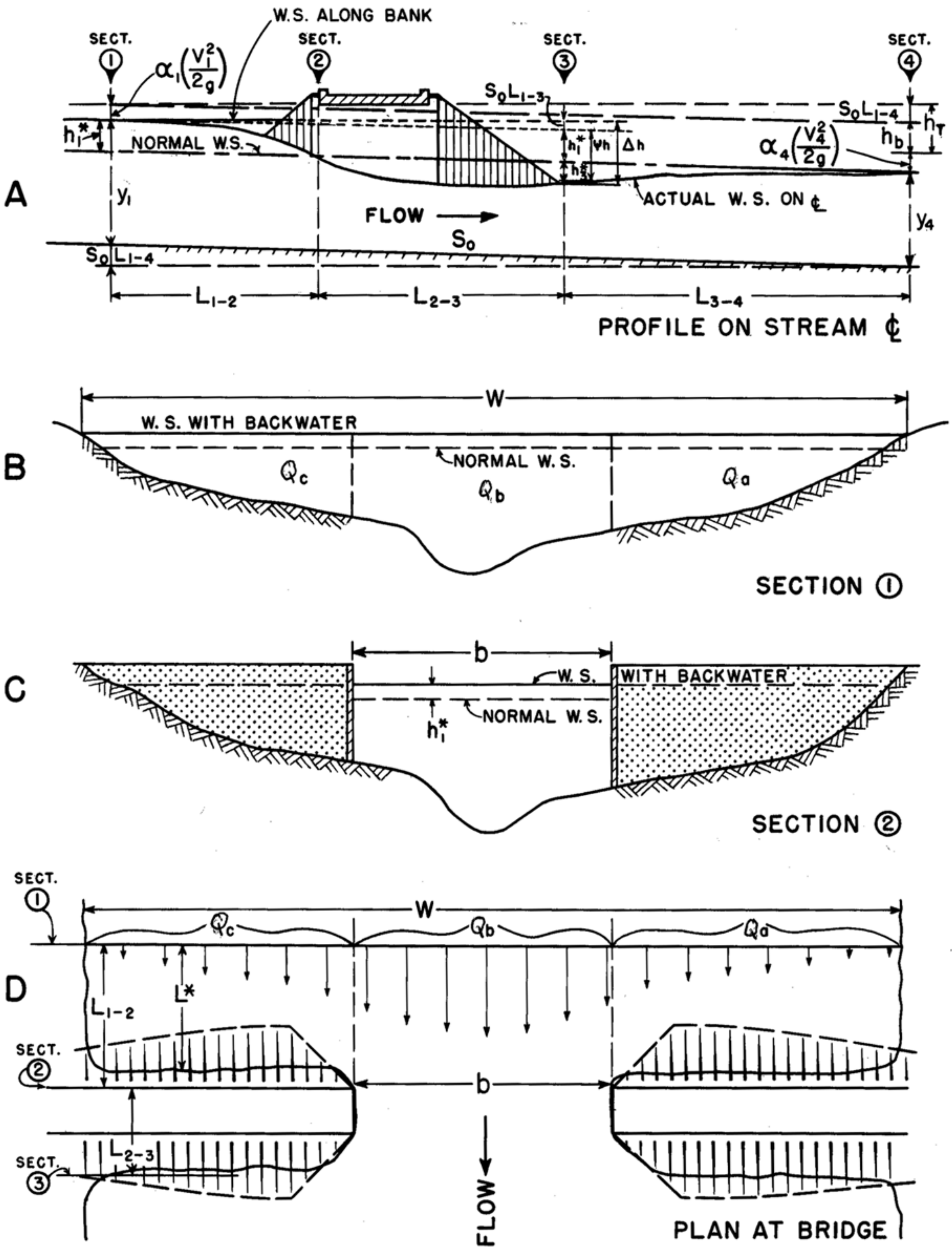

FIGURE 10-1 — Bridge Hydraulics Definition Sketch *(2)*

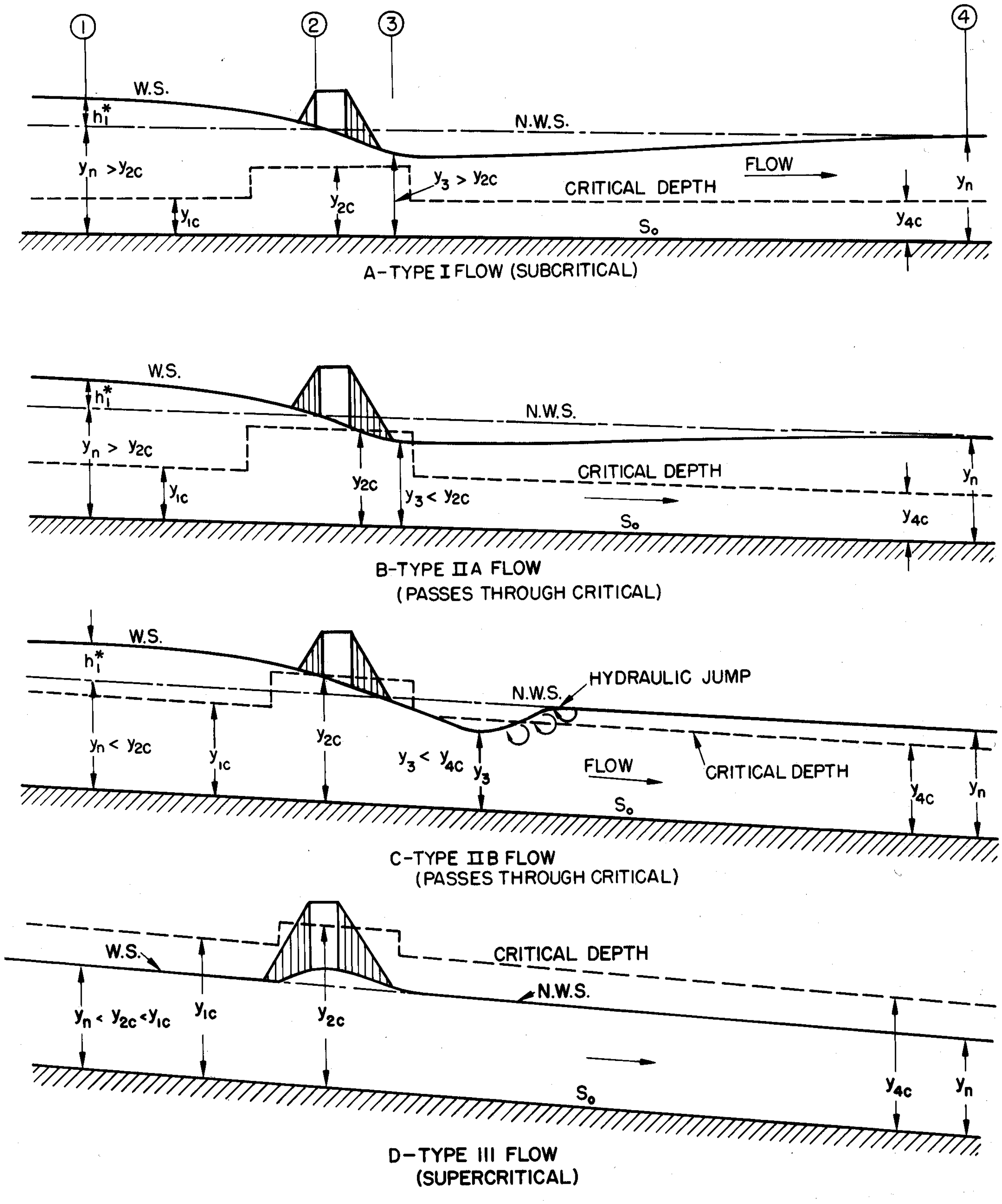

FIGURE 10-2 — Bridge Flow Types *(2)*

10.4.4 Methodologies

No single method is ideally suited for all situations. If a satisfactory computation cannot be achieved with a given method, an alternative method should be attempted. However, it has been found that, with careful attention to the setup requirements of each method, essentially duplicative results can usually be achieved using both momentum and energy methods.

A detailed description of the applicable computer models is not included in this *Manual*. The user manuals for the various computer models should be consulted for program-specific information and for example applications.

10.4.4.1 Momentum (HEC-2)

The USACE HEC-2 model uses a variation of the momentum method in the special bridge routine when there are bridge piers. The momentum equation between Cross Sections 1 and 3 is used to detect Type II flow and solve for the upstream depth in this case with critical depth in the bridge contraction. This program has been used for the majority of the flood insurance studies performed under NFIP.

The HEC-2 computer program was designed to calculate water surface profiles for steady, gradually varied flow using the standard-step method. The program can compute the water surface profiles for different flow rates in a natural stream or a constructed channel. For bridge hydraulics, it models the bridge geometry including pier shape and location, and it predicts different flow situations including low, high and pressurized flows using energy and momentum equations.

10.4.4.2 Momentum (HEC-RAS)

The USACE Hydrologic Engineering Center (HEC) has developed the HEC-RAS (River Analysis System) program package (Reference *(13)*) as the successor to the HEC-2 program *(14)*. HEC-RAS is windows based and uses a Graphical User Interface (GUI) that makes inputting data and viewing output easier and more user friendly.

Some of the benefits to the hydraulics engineer provided by HEC-RAS are:

- computes scour at bridges;
- simulates more culvert shapes (e.g., box, low-profile arch, pipe arch);
- performs calculations on multiple-bridge or culvert openings;
- can compute subcritical and supercritical water surface elevations in one computational step;
- more accurately models bridges than HEC-2 *(14)*; and
- includes provisions for analyzing bridges using WSPRO routines.

10.4.4.3 Energy (HDS 1)

The method developed by FHWA described in HDS 1 *(2)* and Appendix 10.B is an energy approach with the energy equation written between Cross Sections 1 and 4 as shown in Figure

10-1 for Type I flow. The backwater is defined in this case as the increase in the approach water surface elevation relative to the normal water surface elevation without the bridge.

This model utilizes a single, typical cross section to represent the stream reach from Points 1 to 4 on Figure 10-1. It also requires the use of a single energy gradient. This method is no longer recommended for final design analysis of bridges due to its inherent limitations, but it may be useful for preliminary analysis and training. Studies performed by USACE for FHWA show the need to utilize a multiple cross section method of analysis to achieve reasonable stage-discharge relationships at a bridge.

10.4.4.4 Energy (WSPRO)

WSPRO *(11)* is a computer program for water surface computations with special consideration for the design of bridge waterway openings. WSPRO combines step-backwater analysis with bridge backwater calculations. The program provides a powerful computational tool for the analysis of one-dimensional, gradually varied flow profiles through bridge openings. The bridge hydraulics still rely on the energy principle, but there is an improved technique for determining approach flow lengths and the introduction of an expansion loss coefficient. The flow-length improvement was found necessary when approach flows occur on very wide, heavily vegetated floodplains. WSPRO has the ability to analyze multiple openings, roadway overtopping, and orifice and submerged orifice flow, and it contains a design mode option that can size and configure the bridge opening. The program also greatly facilitates the hydraulic analysis required to determine the least-cost alternative.

WSPRO may be used for both preliminary and final analyses of bridge hydraulics. Even if only a single-surveyed cross section is available, the input-data propagation features of WSPRO make it easy to apply, and it provides a comprehensive output.

10.4.4.5 Other Models

The USGS computer model E431 and the NRCS computer model WSP-2 are recognized methods for computing water surface profiles.

10.4.4.6 Two-Dimensional Modeling

The water surface profile and velocities in a section of river are often predicted using a computer model. In practice, most analysis is performed using one-dimensional methods such as the standard-step method found in WSPRO or HEC-RAS. Although one-dimensional methods are adequate for many applications, these methods cannot provide a detailed determination of the cross-stream water surface elevations, flow velocities or flow distribution.

Two-dimensional models are more complex and require more time to set up and calibrate. They require essentially the same field data as a one-dimensional model and, depending on complexity, may require a little more computer time.

USGS has developed a two-dimensional, finite-element model for FHWA that is designated FESWMS *(10)*. FESWMS has been developed to analyze flow at bridge crossings where complicated hydraulic conditions exist. This two-dimensional modeling system is flexible and may be applied to many types of steady and unsteady flow problems, including multiple-opening bridge crossings, spur dikes, floodplain encroachments, multiple channels, flow around islands and flow in estuaries. Where the flow is essentially two-dimensional in the horizontal plane, a one-dimensional analysis may lead to costly over-design or possibly improper design of hydraulic structures and improvements. The USACE RMA2 model is another tool that could be used.

10.4.4.7 Physical Modeling

Complex flow patterns may defy accurate or practicable mathematical modeling. Physical models should be considered when:

- hydraulic performance data are needed that cannot be reliably obtained from mathematical modeling,
- risk of failure or excessive over-design is unacceptable, and
- research is needed.

Constraints on physical modeling are:

- size (scale),
- cost, and
- time.

10.5 BRIDGE SCOUR OR AGGRADATION

10.5.1 <u>Introduction</u>

Reasonable and prudent hydraulic analysis of a bridge design requires that an assessment be made of the proposed bridge's vulnerability to undermining due to potential scour. Because of the extreme hazard and economic hardships posed by a rapid bridge collapse, special considerations must be given to selecting appropriate flood magnitudes for use in the analysis. The hydraulics engineer must always be aware of and use the most current scour forecasting technology.

FHWA issued a Technical Advisory (TA 5140.23) in October 1991 requiring a scour evaluation for existing and proposed bridges over waterways. Refer to HEC 18 *(5)* for a thorough discussion on scour and scour prediction methodology. A companion FHWA document to HEC 18 is HEC 20 *(8).*

The inherent complexities of stream stability, further complicated by highway stream crossings, requires a multilevel solution procedure. The evaluation and design of a highway stream crossing or encroachment should begin with a qualitative assessment of stream stability. This involves application of geomorphic concepts to identify potential problems and alternative solutions. This analysis should be followed with a quantitative analysis using basic hydrologic, hydraulic and sediment transport engineering concepts. Such analyses could include evaluation of flood history, channel hydraulic conditions (up to and including, for example, water surface profile analysis) and basic sediment transport analyses (e.g., evaluation of watershed sediment yield, incipient motion analysis, scour calculations). This analysis can be considered adequate for many locations if the problems are resolved and the relationships between different factors affecting stability are adequately explained. If not, a more complex quantitative analysis, based on detailed mathematical modeling and/or physical hydraulic models, should be considered. This multilevel approach is presented in HEC 20 *(8)*.

Less hazardous perhaps are problems associated with aggradation. Where freeboard is limited, problems associated with increased flood hazards to upstream property or to the traveling public due to more frequent overtopping may occur. Where aggradation is expected, it may be necessary to evaluate these consequences. Also, aggradation in a stream reach may serve to moderate potential scour depths. Aggradation is sometimes referred to as negative scour.

10.5.2 <u>Scour Types</u>

Present technology dictates that bridge scour be evaluated as interrelated components:

- long-term profile changes (aggradation/degradation),
- plan-form change (lateral channel movement),
- contraction scour/deposition, and
- local scour.

10.5.2.1 Long-Term Profile Changes

Long-term profile changes can result from stream bed profile changes that occur from aggradation and/or degradation:

- Aggradation is the deposition of bedload due to a decrease in stream sediment transport capacity that results from a reduction in the energy gradient.

- Degradation is the scouring of bed material due to increased stream sediment transport capacity that results from an increase in the energy gradient.

Forms of degradation and aggradation shall be considered as imposing a permanent future change for the stream bed elevation at a bridge site where they can be identified.

10.5.2.2 Plan-Form Changes

Plan-form changes are morphological changes (e.g., meander migration, bank widening). The lateral movement of meanders can threaten bridge approaches and increase scour by changing flow patterns approaching a bridge opening. Bank widening can cause significant changes in the flow distribution and thus the bridge’s flow contraction ratio.

10.5.2.3 Contraction

Channel contraction scour results from a constriction of the channel that may, in part, be caused by bridge piers in the waterway. Deposition results from an expansion of the channel or the bridge site being positioned immediately downstream of a steeper reach of stream. Highways, bridges and natural channel contractions are the most commonly encountered cause of contraction scour. Two practices are provided in this *Manual* for estimating deposition or contraction scour:

- *Sediment Routing Practice* — This practice should be considered if ((either bed armoring or aggradation from an expanding reach is expected to cause an unacceptable hazard)).

- *Empirical Practice* — This practice is adapted from laboratory investigations of bridge contractions in non-armoring soils and, as such, must be used considering this qualification. This practice does not consider bed armoring, and its application for aggradation may be technically weak.

The algorithms used in this *Manual* to evaluate a naturally contracting reach may also be used to evaluate deposition in an expanding reach provided armoring is not expected to occur. With deposition, the practice of applying the empirical equations “in reverse” is required; i.e., the narrower cross section is upstream, which results in the need to manipulate the use of the empirical “contraction scour” equation. The need to manipulate the equation does not occur with sediment routing practice, which is why the equation may be more reliable in an expanding stream reach.

10.5.2.4 Local Scour

Exacerbating the potential scour hazard at a bridge site are any abutments or piers located within the flood-flow prism. The amount of potential scour caused by these features is termed local scour. Local scour is a function of the geometry of these features as they relate to the flow geometry. However, the importance of these geometric variables will vary. As an example, increasing the pier or cofferdam width either through design or debris accumulation will increase the amount of local scour, but only up to a point in subcritical flow streams. After reaching this point, pier scour should not be expected to measurably increase with increased stream velocity or depth. This threshold has not been defined in the more rare, supercritical flowing streams.

10.5.3 Armoring

Armoring occurs because a stream or river is unable, during a particular flood, to move the more coarse material comprising either the bed or, if some bed scour occurs, its underlying material. Scour may occur initially but later become arrested by armoring before the full scour potential is reached for a given flood magnitude. When armoring does occur, the coarser bed material will tend to remain in place or quickly redeposit to form a layer of riprap-like armor on the stream bed or in the scour holes and thus limit further scour for a particular discharge. This armoring effect can decrease scour hole depths that were predicted based on formulae developed for sand or other fine-material channels for a particular flood magnitude. When a larger flood occurs than used to define the probable scour hole depths, scour will probably penetrate deeper until armoring again occurs at some lower threshold.

If armoring of the stream bed occurs, there may be a tendency for the stream to widen its banks to maintain continuity of sediment transport. This could result in a more unstable, braided regime. Such instabilities may pose serious problems for bridges because they encourage further, difficult-to-assess plan-form changes. Also, the effect of bank widening is to spread the approach flow distribution that, in turn, results in a more severe bridge opening contraction.

10.5.4 Scour-Resistant Materials

Caution is necessary in determining the scour resistance of bed materials and the underlying strata. With sand size material, the passage of a single flood may result in the predicted scour depths. Conversely, in scour-resistant material, the maximum predicted depth of scour may not be realized during the passage of a particular flood; however, some scour-resistant material may be lost. Commonly, this material is replaced with more easily scoured material. Thus, at some later date, another flood may reach the predicted scour depth. Serious scour has been observed to occur in materials commonly perceived to be scour resistant such as consolidated soils and glacial till, so-called bed rock streams and streams with gravel and boulder beds.

10.5.5 Scour Analysis Methods

Before the various scour forecasting methods for contraction and local scour can be applied, it is first necessary to (1) obtain the fixed-bed channel hydraulics, (2) estimate the profile and plan-form scour or aggradation, (3) adjust the fixed-bed hydraulics to reflect these changes, and (4) compute the bridge hydraulics. Two methods are provided in this *Manual* for combining the contraction and local scour components to obtain total scour. Method 1 shall have application where armoring is not a concern or insufficient information is available to permit its evaluation, or where more precise scour estimates are not deemed necessary. Method 2 shall be used when stream bed armoring is of concern, more precise contraction scour estimates are deemed necessary, or deposition is expected and is a primary concern.

10.5.5.1 Method 1

This Method is considered a conservative practice, because it assumes that the scour components develop independently. The potential local scour to be calculated using this Method would be added to the contraction scour without considering the effects of contraction scour on the channel and bridge hydraulics. The general approach with this Method is as follows:

- Estimate the natural channel's hydraulics for a fixed-bed condition based on existing conditions.
- Assess the expected profile and plan-form changes.
- Adjust the fixed-bed hydraulics to reflect any expected profile or plan-form changes.
- Estimate contraction scour using the empirical contraction formula and the adjusted fixed-bed hydraulics assuming no bed armoring. If the reach is expanding, estimate the deposition by "reversing" the empirical equation application and considering deposition as "negative" scour.
- Estimate local scour using the adjusted, fixed-bed channel and bridge hydraulics assuming no bed armoring.
- Add the local scour to the contraction scour or aggradation ("negative" scour) to obtain the total scour.

10.5.5.2 Method 2

This analysis Method is based on the premise that the contraction and local scour components do not develop independently. As such, the local scour estimated with this Method is determined based on the expected changes in the hydraulic variables and parameters due to contraction scour or deposition; i.e., through what may prove to be an iterative process, the contraction scour and channel hydraulics are brought into balance before these hydraulics are used to compute local scour. Additionally, with this Method, the effects of any armoring may also be considered. The general approach for this Method is as follows:

- Estimate the natural channel's hydraulics for a fixed-bed condition based on existing site conditions.
- Estimate the expected profile and plan-form changes based on the procedures in this *Manual* and any historic data.
- Adjust the natural channel's hydraulics based on the expected profile and plan-form changes.
- Select a trial bridge opening and compute the bridge hydraulics.
- Estimate contraction scour or deposition.
- Once again, revise the natural channel's geometry to reflect these contraction scour or deposition changes, and then again revise the channel's hydraulics (repeat this iteration until there is no significant change in either the revised channel hydraulics or bed elevation changes — a significant change would be a 5% or greater variation in velocity, flow depth or bed elevation).
- Using the foregoing revised bridge and channel hydraulic variables and parameters obtained considering the contraction scour or deposition, calculate the local scour.
- Extend the local scour assessment below the predicted contraction scour depths to obtain the total scour.

10.5.6 Scour Assessment Procedure

Bridge scour assessment shall normally be accomplished by collecting the data and applying the general procedure outlined in this Section.

10.5.6.1 Site Data

10.5.6.1.1 Bed Material

Obtain bed material samples for all channel cross sections when armoring is to be evaluated. If armoring is not being evaluated, this information need only be obtained at the site. From these samples, try to identify historical scour and associate it with a discharge. Also, determine the bed material size distribution in the bridge reach and, from this distribution, determine d_{16}, d_{50}, d_{84} and d_{90}.

10.5.6.1.2 Geometry

Obtain floodplain cross sections, stream profile, site plan and the stream's present and any available historic geomorphic information. Also, locate the bridge site with respect to such features as other bridges in the area, tributaries to the stream or close to the site, bed rock controls, man-made controls (dams, old check structures and river training works) and downstream confluence with other streams. Locate (distance and height) any "headcuts" due to natural causes or such activities as gravel mining operations. Upstream gravel mining operations may absorb the bed material discharge resulting in the more adverse clear water scour case discussed later. Any data related to plan-form changes (e.g., meander migration, rate at which they may be occurring) are useful.

10.5.6.1.3 Historic Scour

Obtain any scour data on other bridges or similar facilities along the stream.

10.5.6.1.4 Hydrology

Identify the character of the stream hydrology; i.e., perennial, ephemeral, intermittent and whether it is “flashy” or subject to broad hydrograph peaks resulting from gradual flow increases such as occur with slow-moving storms or snowmelt.

10.5.6.1.5 Geomorphology

Classify the geomorphology of the site; i.e., such factors as whether it is a floodplain stream, crosses a delta or crosses an alluvial fan; youthful, mature or old age.

10.5.6.2 General

Step 1 Decide which analysis method is applicable. Method 2 shall be used to evaluate bridges where armoring or an expanding reach are of concern and where Method 1 indicates a significant potential scour hazard may exist.

Step 2 Determine the magnitude of the base flood and “super flood” and the magnitude of the incipient overtopping flood or relief opening flood. Accomplish Steps 3 through 12 using the discharge that places the greatest stress on the bed material in the bridge opening.

Step 3 Determine the bed material size that will resist movement and cause armoring to occur.

Step 4 Develop a water surface profile through the site’s reach for fixed-bed conditions.

It should now be possible to establish a water surface profile and perform subsequent bed-form change and/or bridge scour calculations with a single tool. Both the USACE “HEC-RAS” and the NCHRP’s “BRI-STARS” *(4)* software packages are intended for just such an application. Both include quasi two-dimensional flow, sediment transport and scour analysis capabilities while also establishing a water surface profile.

Step 5 Assess the bridge crossing reach of the stream for profile bed scour changes to be expected from degradation or aggradation. Again, consider past, present and future conditions of the stream and watershed to forecast what the elevation of the bed might be in the future. Certain plan-form changes (e.g., migrating meanders causing channel cutoffs) would be important in assessing future streambed profile elevations. The possibility of downstream mining operations inducing “headcuts” shall be considered. The quickest way to assess streambed elevation changes due to “headcuts” (degradation) is by obtaining a vertical measurement of the downstream “headcut(s)” and projecting that measurement(s) to the bridge site using the existing stream profile assuming that the stream is in the same regime as the headcut; if it is not, then it may be necessary to estimate the regime slope. A more time-consuming way to assess elevation changes would be to use some form of sediment routing practice in conjunction with a synthetic flood history.

Step 6 Assess the bridge crossing reach of the stream for plan-form scour changes. Attempt to forecast whether an encroaching meander will cause future problems within the expected service life of the road or bridge. Consider past, present and expected future conditions of the stream and watershed to forecast how such meanders might influence the approach flow direction in the future. The sediment routing practice for computing channel contraction scour or aggradation may prove useful in making such assessments — particularly if coupled to a synthetic flood history. This forensic analysis on a site’s past geomorphological history to forecast the future may prove useful. Otherwise, this assessment has to be largely subjective in nature.

Step 7 Based on the expected profile and plan-form scour changes, adjust the fixed-bed hydraulic variables and parameters.

Step 8 Assess the magnitude of channel or bridge contraction scour using Method 1 or Method 2 based on the fixed-bed hydraulics of Step 7.

Step 9 Assess the magnitude of local scour at abutments and piers using Method 1 or Method 2.

Step 10 Plot the scour and aggradation depths from foregoing Steps on a cross section of the stream channel and floodplain at the bridge site. Using judgment, enlarge any overlapping scour holes. Treat any aggradation as a negative scour.

Step 11 Evaluate the findings of Step 10. If the scour is unacceptable, consider the use of scour countermeasures, or revise the trial bridge opening and repeat the foregoing Steps.

Step 12 Once an acceptable scour threshold is determined, the geotechnical engineer can make a preliminary foundation design for the bridge based on the scour information obtained from the foregoing procedure and using commonly accepted safety factors. The structural engineer should evaluate the lateral stability of the bridge based on the foregoing scour.

Step 13 Repeat the foregoing assessment procedures using the greatest bridge opening flood discharge associated with the selected “super flood”. These findings are again for the geotechnical engineer to use in evaluating the foundation design obtained in Step 12. A foundation design safety factor of 1.0 is commonly used to ensure that the bridge is marginally stable for a flood associated with the “super flood”.

10.5.7 Pressure Flow Scour

Pressure flow, which is also denoted as orifice flow, occurs when the water surface elevation at the upstream face of the bridge is greater than or equal to the low chord of the bridge superstructure. Pressure flow under the bridge results from a pile up of water on the upstream bridge face and a plunging of the flow downward and under the bridge. At higher approach flow depths, the bridge can be entirely submerged with the resulting flow being a complex combination of the plunging flow under the bridge and the flow over the bridge.

With pressure flow, the local scour depths at a pier or abutment are larger than for free surface flow with similar depths and approach velocities. The increase in local scour at a pier subject to pressure flow results from the flow being directed downwards toward the bed by the superstructure and by increasing the intensity of the horseshoe vortex. The vertical contraction of the flow is a more significant cause of the increase in scour depth. However, in many cases, when a bridge becomes submerged, the average velocity under it is reduced due to a combination of additional backwater caused by the bridge superstructure impeding the flow and a reduction of discharge that must pass under the bridge due to weir flow over the bridge and approach embankments. As a consequence, increases in local scour attributed to pressure flow scour at a particular site may be offset to a degree by lesser velocities through the bridge opening due to increased backwater and a reduction in discharge under the bridge due to overtopping.

WSPRO or HEC-RAS can be used to determine the discharge through the bridge and the velocity of approach and depth upstream of the piers when flow impacts the bridge superstructure. These values should be used to calculate local pier scour. Engineering judgment will then be exercised to determine the appropriate multiplier times the calculated pier scour depth for the pressure flow scour depth. This multiplier ranges from 1.0 for low approach Froude numbers (Fr = 0.1) to 1.6 for high approach Froude numbers (Fr = 0.6). If the bridge is overtopped, the depth to be used in the pier scour equations and for computing the Froude number is the depth to the top of the bridge deck or guardrail obstructing the flow.

10.5.8 Tidal Scour

The analysis of tidal waterways is very complex. The hydraulics engineer must consider the magnitude of the 100-yr and the 500-yr storm surge, the characteristic of the tidal body, and the effect of any constriction of the flow due to natural geometry of the waterway or the presence of a roadway and bridge. In addition, the hydraulics engineer must consider the longer effects of the normal tidal cycles or long-term aggradation or degradation, contraction scour, local scour and stream instability.

A three-level approach to the analysis of bridge crossings of tidal waterways should be considered, similar to those outlined in HEC 20 *(8)*. Level 1 includes a qualitative evaluation of the stability of the waterway, an estimate of the magnitude of tides and storm surges and flow in the tidal waterway. Level 2 involves an engineering analysis to obtain velocities, flow depths, discharge and scour depths for the tidal waterway. A Level 3 analysis requires a physical model or a two-dimensional mathematical model.

At the present time, no suitable scour equations have been developed specifically for tidal flows. Because of this, it is recommended that the scour equations developed for inland rivers be used to estimate and evaluate the tidal scour. The FESWMS (Finite Element Surface Water Model System), a two-dimensional flow computer simulation model, can be used to predict tidal action.

HEC 18 *(5)* provides recommended procedures for the hydraulic evaluation of a tidal crossing.

10.6 PHILOSOPHY

10.6.1 Introduction

Any stream is a dynamic natural system that, as a result of the encroachment caused by elements of a stream-crossing system, will respond in a way that may well challenge even an experienced hydraulics engineer. The complexities of the stream response to encroachment demand that (1) hydraulics engineers must be involved from the outset in the choice of alternative stream-crossing locations, and (2) at least some of the members of the engineering design team must have extensive experience in the hydraulic design of stream-crossing systems. Hydraulics engineers should also be involved in the solution of stream stability problems at existing structures.

This Section discusses qualitatively some of the design issues that contribute to the overall complexity of spanning a stream with a stream-crossing system. A much more thorough discussion of design philosophy and design considerations is found in Reference *(1).*

10.6.2 Location of Stream Crossing

Although many factors, including nontechnical ones, enter into the final location of a stream-crossing system, the hydraulics of the proposed location must have a high priority. Hydraulic considerations in selecting the location include floodplain width and roughness, flow distribution and direction, stream type (braided, straight or meandering), stream regime (aggrading, degrading or equilibrium) and stream controls. The hydraulics of a proposed location also affect environmental considerations (e.g., aquatic life, wetlands, sedimentation, stream stability). Finally, the hydraulics of a particular site determine whether or not certain national objectives, such as the wise use of floodplains, reduction of flooding losses and preservative of wetlands, can be met.

10.6.3 Coordination, Permits and Approvals

The interests of other governmental agencies must be considered in the evaluation of a proposed stream-crossing system, and cooperation and coordination with these agencies, especially water resources planning agencies, must be undertaken. Coordination with FEMA is required when a:

- proposed crossing encroaches on a regulatory floodway and would require an amendment to the floodway map;
- proposed crossing encroaches on a floodplain where a detailed study has been performed but no floodway has been designated and the maximum 1-ft increase in the base flood would be exceeded;
- community is expected to enter into the regular program within a reasonable period and detailed floodplain studies are underway; and
- community is participating in the emergency program and the base flood elevation in the vicinity of insurable buildings is increased by more than 1 ft.

When practicable, the stream-crossing system shall avoid encroachment on the floodway within a floodplain. When this is not feasible, modification of the floodway itself shall be considered. If neither of these alternatives is feasible, FEMA regulations for “floodway encroachment where demonstrably appropriate” shall be met.

Designers of stream-crossing systems must be cognizant of relevant local, State and Federal laws and permit requirements. Federal permits are required for the construction of bridges over navigable waters and are issued by USCG. Permits for other construction activities in navigable waters are under the jurisdiction of USACE. Applications for Federal permits may require environmental impact assessments under the National Environmental Policy Act of 1969. Environmental Considerations

Environmental criteria that must be met in the design of stream-crossing systems include the preservation of wetlands and protection of aquatic habitat. Such considerations often require the expertise of a biologist on the design team. Water quality considerations shall also be included in the design process insofar as the stream-crossing system affects the water quality relative to beneficial uses. As a practical matter with bridges, the hydraulic design criteria related to scour, degradation, aggradation, flow velocities and lateral distribution of flow, for example, are important criteria for evaluation of environmental impacts and the safety of the stream-crossing structures. Environmental consequences of the bridge construction activity must also be considered (see Section 10.6.11).

10.6.4 <u>Stream Morphology</u>

The form and shape of the stream path created by its erosion and deposition characteristics comprise its morphology. A stream can be braided, straight or meandering, or it can be in the process of changing from one form to another as a result of natural or man-made influences. A historical study of the stream morphology at a proposed stream-crossing site is mandatory. (FHWA HEC 20 *(8)* Level I Analysis). This study shall also include an assessment of any long-term trends in aggradation or degradation. Braided streams and alluvial fans shall especially be avoided for stream-crossing sites where possible.

10.6.5 <u>Data Collection</u>

The purpose of data collection is to gather all necessary site information. This shall include such information as topography and other physical features, land use and culture, flood data, basin characteristics, precipitation data, historical high-water marks, existing structures, channel characteristics and environmental data. A site plan shall be developed on which much of the data can be shown. Refer to Chapter 6 for additional data collection information.

10.6.6 <u>Risk Evaluation</u>

The evaluation of the consequence of risk associated with the probability of flooding attributed to a stream-crossing system is a tool by which site-specific design criteria can be developed. This evaluation considers capital cost, traffic service, environmental and property impacts and hazards to human life.

The evaluation of risk is a two-stage process. The initial step, identified as risk assessment, is more qualitative than a risk analysis and serves to identify threshold values that must be met by the hydraulic design. A “Preliminary Risk Assessment Form” to be used for documenting this assessment is presented in Appendix 10.A.

In many cases, where the risks are low and/or threshold design values can be met, it is unnecessary to pursue a detailed economic analysis. In those cases where the risks are high and/or threshold values cannot be met, a Least Total Expected Cost (LTEC) analysis should be considered.

The results of a least-cost analysis can be presented in a graph of total cost as a function of the overtopping discharge. The total cost consists of a combination of capital costs and flood damages (or risk costs). Risk costs decrease with increases in the overtopping discharge while capital costs simultaneously increase. The overtopping discharge for each alternative is determined from a hydraulic analysis of a specific combination of embankment height and bridge-opening length. The resulting least-cost alternative provides a tradeoff comparison. If, for example, environmental criteria result in an alternative that is different from the least-cost alternative, the economic tradeoff cost of that alternative can be given as the difference between its cost and the minimum cost provided by a LTEC analysis.

The alternatives considered in the least-cost analysis do not require the specification of a particular design flood. This information is part of the output of the least-cost analysis. In other words, the least-cost alternative has a specific risk of overtopping that is unknown before the least-cost alternative has been determined. Therefore, design flood frequencies are used only to establish the initial alternative. Thereafter, specific flood-frequency criteria (e.g., the 50-yr flood requirement for certain Interstate highways, the 100-yr floodplain requirements for FEMA flood insurance) should be considered only as constraints on the final design selection. Deviation from the least-cost alternative may be necessary to satisfy these constraints, and the tradeoff cost for doing so can be obtained from the least-cost analysis.

Risk-based analysis does not recognize some of the intangible factors that influence a design. The minimum design that results from this type of analysis may be too low to satisfy the site condition.

10.6.7 Scour

The extreme hazard posed by bridges subject to bridge scour failures dictates a different philosophy in selecting suitable flood magnitudes to use in the scour analysis. With bridge flood hazards other than scour (e.g., those caused by roadway overtopping, property damage from inundation), a prudent and reasonable practice is to first select a design flood to determine a trial bridge opening geometry. This geometry is either subjectively or objectively selected based on the initial cost of the bridge along with the potential future costs for flood hazards. Following the selection of this trial bridge geometry, the base flood (100-yr) is used to evaluate this selected opening. This two-step evaluation process is used to ensure that the selected bridge opening based on the design flood contains no unexpected increase in any existing flood hazards other than those from scour or aggradation. With bridge scour, not only is it required to consider bridge scour or aggradation from the base flood, but also the 500-yr flood termed herein as the “super flood”.

Scour prediction technology is steadily developing, but lacks at this time, the reliability associated with other facets of hydraulics engineering. Several formulae for predicting scour depths are currently available, and others will certainly be developed in the future. The hydraulics engineer should strive to be acquainted with the “state of practice” at the time of a given analysis and is encouraged to be conservative in the resulting scour predictions.

First, discussion is warranted as to what constitutes the greatest discharge passing through the bridge opening during a particular flood. Even where there are relief structures on the floodplain or overtopping occurs, some flood other than the base flood or “super flood” may cause the worse-case bridge opening scour. This situation occurs where the bridge opening will pass the greatest discharge just prior to overtopping or flood flow through a relief opening. Should this occur, the incipient overtopping flood would be used to evaluate the bridge scour.

With potential bridge scour hazards, a different flood selection and analysis philosophy is considered reasonable and prudent. The foregoing trial bridge opening that was selected by considering initial costs and future flood hazard costs shall be evaluated for two possible scour conditions with the worse-case dictating the foundation design — and possibly a change in the selected trial bridge opening.

First, evaluate the proposed bridge and road geometry for scour using the base flood, incipient overtopping flood, overtopping flood corresponding to the base flood or the relief opening flood, whichever provides the greatest flood discharge through the bridge opening. Once the expected scour geometry has been assessed, the geotechnical engineer would design the foundation. This foundation design would use the conventional foundation safety factors and eliminate consideration of any stream bed and bank material displaced by scour for foundation support.

Second, impose a “super flood” on the proposed bridge and road geometry. This event shall be used to evaluate the proposed bridge opening to ensure that the resulting potential scour will produce no unexpected scour hazards. Similar to the base flood to evaluate the selected bridge opening, use either the “super flood” or the relief opening flood, whichever imposes the greatest flood discharge on the selected bridge opening. The foundation design based on the base flood would then be reviewed by the geotechnical engineer using a safety factor 1.0 and, again, considering any stream bed and bank material displaced by scour from the “super flood”.

10.6.8 Preventive/Protection Measures

Based on an assessment of potential scour provided by the hydraulics engineer, the structural engineer can incorporate design features that will prevent or mitigate scour damage at piers. In general, circular piers or elongated piers with circular noses and an alignment parallel to the flood-flow direction are a possible alternative. Spread footings should be used only where the stream bed is extremely stable below the footing and where the spread footing is founded at a depth below the maximum scour computed in Section 10.6.8. Drilled shafts or drilled piers are possible where pilings cannot be driven. Protection against general stream bed degradation can be provided by drop structures or grade-control structures in, or downstream of, the bridge opening.

Rock riprap is often used, where stone of sufficient size is available, to armor abutment fill slopes and the area around the base of existing piers. Riprap design information is presented in Appendix 10.B, Section 10.B.1.2. HEC 23 and NCHRP Project No. 24-7(2) “Countermeasures to Protect Bridge Piers from Scour” discuss other materials that may be used to abate scour.

Where possible, clearing of vegetation upstream and downstream of the toe of the embankment slope should be avoided. Roadway overtopping may be incorporated into the design but should be located well away from the bridge abutments and superstructure. Spur dikes are recommended to align the approach flow with the bridge opening and to prevent scour around the abutments. They are usually elliptical shaped with a major to minor axis ratio of 2.5 to 1. Some States have found that a length of approximately 150 ft provides a satisfactory standard design. Their length can be determined according to HDS 1 *(2)*. Spur dikes, embankments and abutments shall be protected by rock riprap with a filter blanket or other revetments approved by the Department.

10.6.9 Deck Drainage

Where it is necessary to intercept deck drainage at intermediate points along the bridge, the design of the interceptors shall conform to the procedures presented in Chapter 13, HEC 21 *(6)* and HEC 22 *(9)*.

10.6.10 Construction/Maintenance

Construction plans should be reviewed jointly by the Contractor and the Department's Hydraulics Engineer to note any changes in the stream from the conditions used in the design. Temporary structures and crossings used during construction should be designed for a specified risk of failure due to flooding during the construction period. The impacts on normal water levels, fish passage and normal flow distribution must be considered.

All borrow areas existing within the floodplain shall be chosen to minimize the potential for scour and adverse environmental effects within the limits of the bridge and its approaches on the floodplain.

The stream-crossing design shall incorporate measures that reduce maintenance costs where possible. These measures include spur dikes, retards, guide dikes, jetties, riprap protection of abutments and embankments, embankment overflow at lower elevations than the bridge deck, and alignment of piers with the flow.

10.6.11 Waterway Enlargement

There are situations where roadway and structural constraints dictate the vertical positioning of a bridge and result in a small vertical clearance between the low chord and the ground. Significant increases in span length provide small increases in effective waterway opening in these cases.

It is possible to increase the effective area by excavating a flood channel through the reach affecting the hydraulic performance of the bridge. There are, however, several factors that must be accommodated when this action is taken:

- The flow line of the flood channel should be set above the stage elevation of the dominant discharge (see Reference *(1)*).
- The flood channel must extend far enough up and downstream of the bridge to establish the desired flow regime through the affected reach.
- The flood channel must be stabilized to prevent erosion and scour.

10.6.12 Auxiliary Openings

The need for auxiliary waterway openings, or relief openings as they are commonly termed, arises on streams with wide floodplains. The purpose of openings on the floodplain is to pass a portion of the flood flow in the floodplain when the stream reaches a certain stage. It does not provide relief for the principal waterway opening in the sense that an emergency spillway at a dam does, but it has predictable capacity during flood events. However, the hydraulics engineer should be aware that the presence of overtopping or relief openings may not result in a significant reduction in flow through the bridge opening.

Basic objectives in choosing the location of auxiliary openings include:

- maintenance of flow distribution and flow patterns,
- accommodation of relatively large flow concentrations on the floodplain,
- avoidance of floodplain flow along the roadway embankment for long distances,
- crossing of significant tributary channels, and
- accommodation of eccentric stream crossings.

The technological weakness in modeling auxiliary openings is in the use of one-dimensional models to analyze two-dimensional flow. Two-dimensional models (e.g., FESWMS) should provide a more adequate analysis of complex stream-crossing systems.

The most complex factor in designing auxiliary openings is determining the division of flow between the two or more structures. If incorrectly proportioned, one or more of the structures may be overtaxed during a flood event. The design of auxiliary openings should usually be generous to guard against that possibility.

10.7 REFERENCES

(1) AASHTO, *Highway Drainage Guidelines*, Chapter 7, "Hydraulic Analysis for the Location and Design of Bridges," AASHTO Task Force on Hydrology and Hydraulics, 2003.

(2) Bradley, J.N., *Hydraulics of Bridge Waterways*, Hydraulic Design Series No. 1, FHWA-EPD-86-101, Federal Highway Administration, 1978.

(3) Corry, M.L., Jones, J.S. and Thompson, P.L., *Design of Encroachments on Floodplains Using Risk Analysis*, Hydraulic Engineering Circular No. 17, Federal Highway Administration, Washington, DC, 1981.

(4) Federal Highway Administration, *BRI-STARS Users Manual, Bridge Stream Tube for Alluvial River Simulation* (Version 5.03), FHWA-RD-99-190 & 1, 2000.

(5) Federal Highway Administration, *Evaluating Scour at Bridges*, Hydraulic Engineering Circular No. 18, FHWA-NHI-01-001, 2001.

(6) Federal Highway Administration, Hydraulic Engineering Circular No. 21, *Bridge Deck Drainage System*, FHWA-SA-92-010, 1993.

(7) Federal Highway Administration, *River Engineering for Highway Encroachments — Highways in the River Environment*, Hydraulic Design Series No. 6, FHWA-NHI-01-004, December 2001.

(8) Federal Highway Administration, *Stream Stability at Highway Structures*, Hydraulic Engineering Circular No. 20, FHWA-NHI-01-002, 2001.

(9) Federal Highway Administration, *Urban Drainage Design Manual*, Hydraulic Engineering Circular No. 22, FHWA-NHI-01-021, 2001.

(10) Federal Highway Administration, *User's Manual for FESWMS – Flo2DH (2-dimensional depth-average flow and sediment transport model)*, Version 3, FHWA-RD-03-053, 2003.

(11) Federal Highway Administration, *WSPRO User's Manual* (Version P60188), FHWA-SA-98-080, 1999.

(12) US Army Corps of Engineers, "Accuracy of Computed Water Surface Profiles," December 1986.

(13) US Army Corps of Engineers, *HEC-RAS River Analysis System, User's Manual*, The Hydrologic Engineering Center, Davis, CA, Version 3.0, January 2001.

(14) US Army Corps of Engineers, HEC-2 Water Surface Profiles, *User's Manual*, Version 4.6, September 1990.